Axions++ 2023

New solar X-ray constraints on keV ALPs and Kaluza-Klein axions

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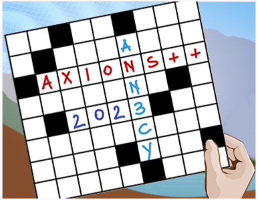
Presentation based on arXiv 2107.13337 and 2303.06968



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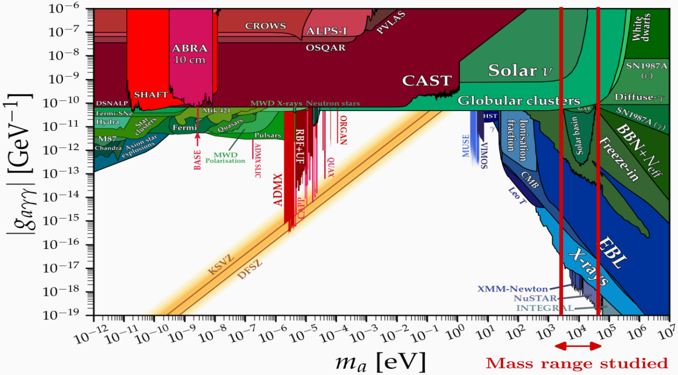
Outline

PART 1: Trapped axions

PART 2: Solar constraints on standard Axion-Like Particles (ALPs)

PART 3: Solar constraints on Kaluza-Klein axions (= higher-dimensional axions)

Trapped axions



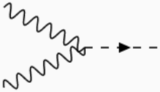
C. O'Hare's github

We study axions with masses of order $m \in [3,\ 40\ \text{keV}] \implies$ **astrophysical constraints**

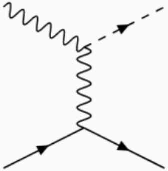
- We assume that the ALPs do not account for the entire dark matter density $\implies$ releases the constraints
- The Kaluza-Klein axions can escape the astrophysical constraints $\implies$ **viable dark matter candidate**

The Sun can produce axions with masses up to few tens of keV

Hadronic axions
Parametrized by $g_{a\gamma\gamma}$

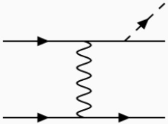


Photon coalescence

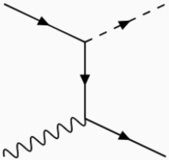


Primakoff

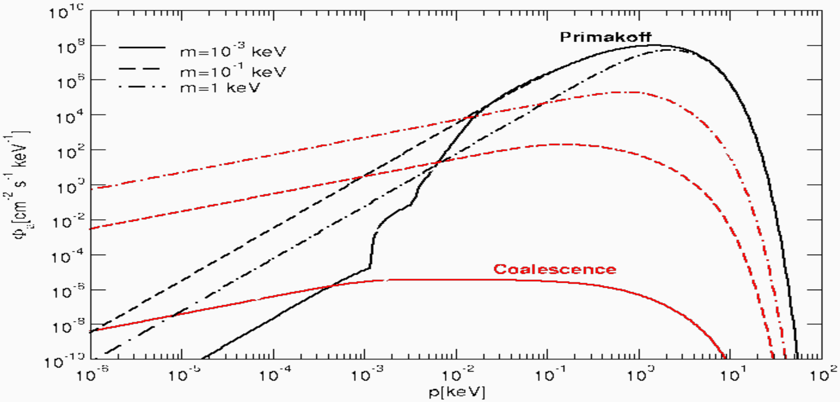
Non-hadronic axions
Parametrized by g_{ae}



Bremsstrahlung



Compton



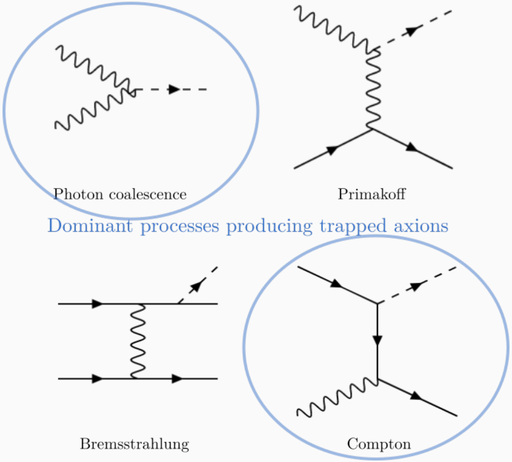
Differential axion fluxes at Earth for $g_{a\gamma\gamma} = 10^{12}\ \mathrm{GeV}^{-1}$.

$\Longrightarrow$ The axion production via the photon coalescence dominates over the Primakoff production **for low momenta**

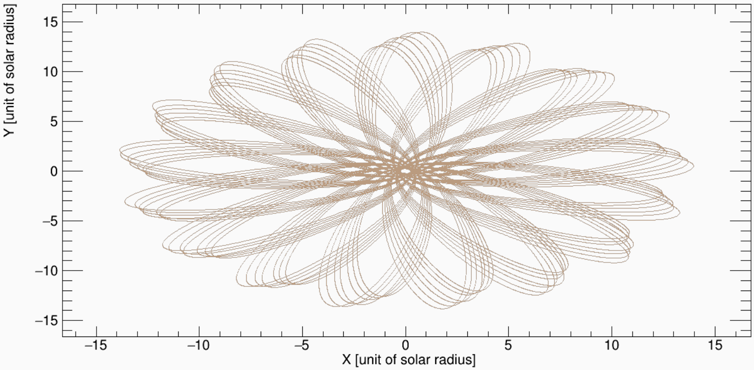
The Sun can produce axions with masses up to few tens of keV

Hadronic axions
Parametrized by $g_{a\gamma\gamma}$

Non-hadronic axions
Parametrized by g_{ae}



When $v_a < v_{esc.}^{Sun}$, the axion gets **gravitationnally bounded** to the Sun $\Longleftrightarrow$ Trapped axion

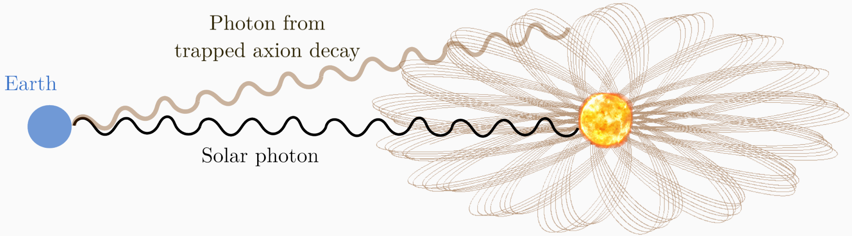


Example of the orbit of a trapped axion

Accumulate over cosmic times!

Increase the detection event rates on Earth by more than 2 orders of magnitude with respect to the direct axion flux.

A trapped axion can decay into two photons with identical energy of $E_\gamma = m_a/2$.



Solar X-ray constraint:

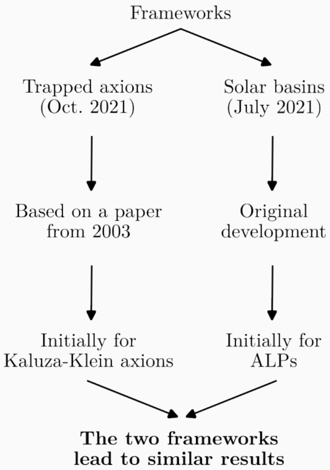
- The decays of trapped axions contribute to the observed solar luminosity
- The axion-induced photon flux should not exceed the measured solar flux

$\Longrightarrow$ **We set limits on keV axions** by comparing our predictions to the solar X-ray data collected by SphinX with $E_\gamma \in [1.5, 6 \text{ keV}]$ and by NuSTAR with $E_\gamma \in [3, 20 \text{ keV}]$

$\Longrightarrow$ **This method does not rely on any assumption about the local dark matter density**

Solar constraints on standard ALPs

Two frameworks have been developed **independently and simultaneously**



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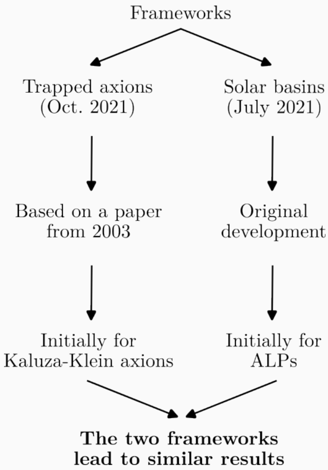

The *solar basin* framework has been used to set constraints on ALPs in a paper from DeRocco *et al.*


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First Indirect Detection Constraints on Axions in the Solar Basin

William DeRocco,[1,*] Shalma Wegsman,[2,†] Brian Grefenstette,[3,‡] Junwu Huang,[4,§] and Ken Van Tilburg[2,5,∥]
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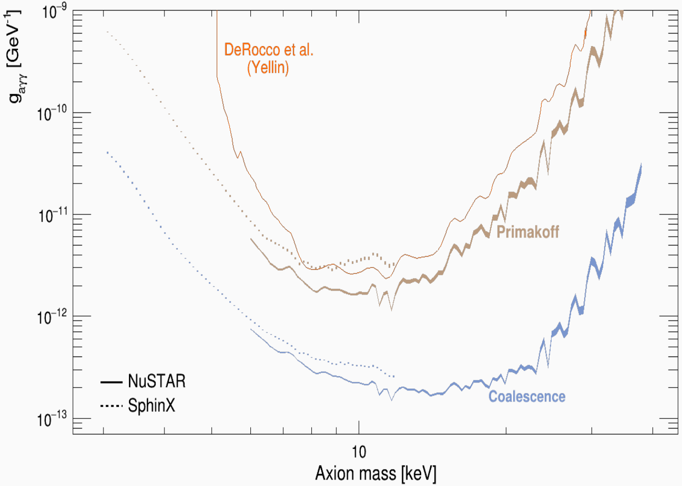
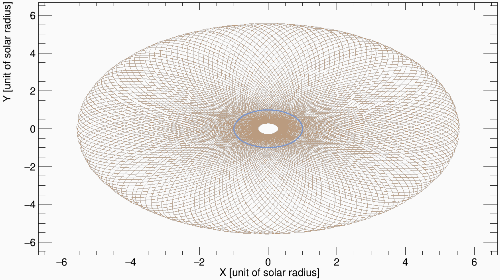
$\Longrightarrow$ We decided to use our framework to reproduce the DeRocco et al. results with two main novelties:

- Add another production mechanism
- Consider some axion-absorption in the Sun

The coalescence of two photons is the dominant process for producing trapped axions from the $g_{a\gamma\gamma}$ coupling. We added this mechanism that was omitted in DeRocco et al.'s work.

$\Longrightarrow$ **Improves the constraints by one order of magnitude**

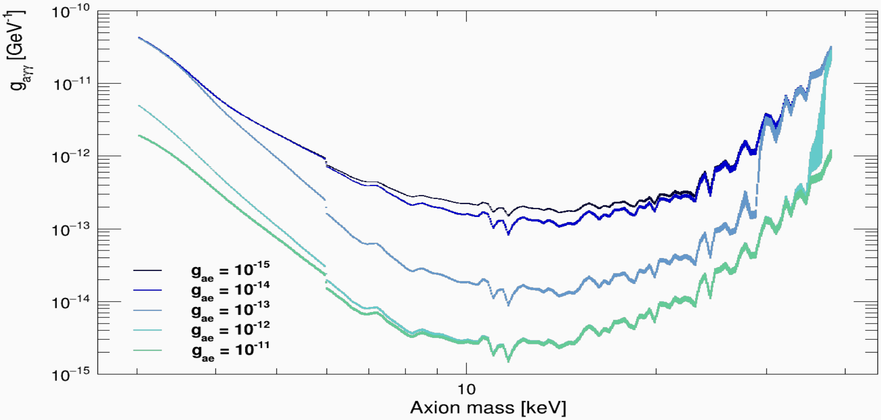




Example of a trapped axion tracked for a year.
The solar surface is represented in blue.

The trapped axions frequently cross the Sun in their orbits. For non-hadronic axions, meaning **for $g_{ae} \neq 0$, the axions can produce a Compton scattering with the electrons in the core of the Sun and be absorbed.**

$\Longrightarrow$ **We derived the probability of such an absorption, both analytically and by means of a MC simulation.**



$\Longrightarrow$ Out of the transitional region,
the solar X-ray constraints on ALPs are exclusively governed by $g_{a\gamma\gamma}$.

Solar constraints on Kaluza-Klein axions

Large extra spatial dimensions:

- Introduce n extra spatial dimensions **compactified** with a radius $R \lesssim 10\,\mu\text{m}$
- The axion can propagate in the extra dimensions
- The SM fields are confined into the 4D brane

Credit: T. Banchoff

Why such a framework?

- Theoretically motivated to solve the hierarchy problem (among other features)
- Why not? ;) $\longrightarrow$ **extra spatial dimensions are experimentally allowed**

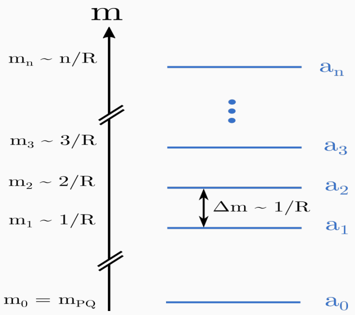
Axion in extra dimensions:

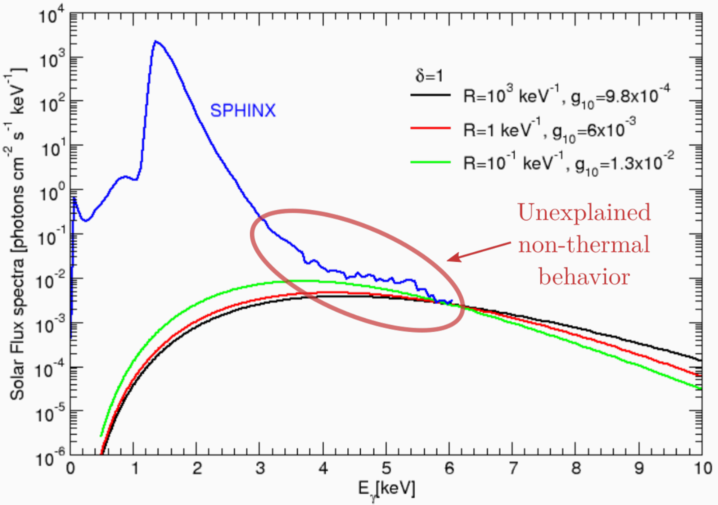
From our 4-dimensional world, the $(4+\delta)$-axion is seen as an almost infinite superposition of state called a **Kaluza-Klein (KK) tower**

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4} a\, F^{\mu\nu}\tilde{F}_{\mu\nu} \xrightarrow[\text{from 4D brane}]{(4+\delta)\text{ axion seen}} \frac{g_{a\gamma\gamma}}{4}\left(\sum_n r_n a_n\right) F^{\mu\nu}\tilde{F}_{\mu\nu}$$

Consequences:

- Large mode multiplicity
- **Lifetimes comparable to the age of the Universe**
- The ground state of the KK tower is the only state to obey the Peccei-Quinn mechanism $\Longrightarrow$ **identified as the QCD axion**





The solar X-ray measurements set stringent limits on $g_{a\gamma\gamma}$ for every set of extra-dimensional parameters.

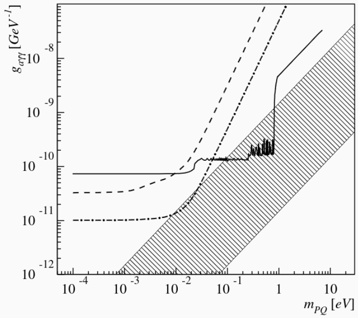
The decay of trapped KK axions into photons, which produces a continuous energy spectrum, **could explain the non-thermal behavior of the solar X-rays.**

Direct Dark Matter Detectors :

Several direct DM detectors have searched for KK axions (XMASS, NEWS-G, DRIFT). Our model revision and **our new solar X-ray constraints reduce by 6 orders of magnitude the event rate in such detectors**, closing the window for detection...

Other strategies of detection:

Helioscopes, haloscopes, LSW experiments and detection through nuclear transitions are several strategies able to search for KK axions. In some case, **the data collected for QCD axion searches can be re-analysed to search for KK axions, without modifying the design of the detector.**



CAST limits on KK axions. R. Horvat et al., Phys. Rev. D 69, 2004

Conclusion

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Take home messages:

- In the keV-range, the phenomenology of solar axion in governed by trapped axions
- The photon coalescence is an important process for the production of non-relativistic axions
- Extra-dimensional axions (KK axions) could explain the non-thermal behavior of the solar X-ray spectrum
- Some axion detectors could also search for KK axions

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Thank you for your attention!